Solar Spectroscopy: Atomic Processes

A Greek philosopher called DEMOCRITUS (*c*. 460–370 BC) first introduced the concept of atoms (which means indivisible). His atoms do not precisely correspond to our atoms of today, which are not indivisible, but made up of a nucleus (protons with positive charge and neutrons which have no charge) and orbiting electrons (with negative charge). Indeed, in the solar atmosphere, the temperature is such that atoms are often ionized (to form ions), that is they have lost one electron or two or more. It is the interaction of the atoms and ions with electrons, protons and the radiation field which we refer to as atomic processes. These atomic processes in a PLASMA (ionized gas) determine the intensity or brightness of the radiation which we observe at all wavelengths from the SOLAR ATMOSPHERE. In particular, the transitions give rise to emission and absorption spectral lines.

The birth of quantum mechanics

In 1900, MAX PLANCK presented a derivation of the black-body law in Germany, and the theory of quantum physics was born. In his derivation for the intensity of radiation as a function of wavelength and temperature, Planck set aside classical physics and made an *ad hoc* assumption that light energy, E, was emitted and absorbed in packets (photons) ($E = h\nu$) by oscillators with a natural frequency, ν, where h is a fundamental constant of nature, now known as Planck's constant. Planck himself was not at all happy with his own idea, and he tried for many years to disprove it and understand black-body radiation with classical physics. The radiation from the SOLAR PHOTOSPHERE can be approximated to a black body of temperature just below 6000 K.

ALBERT EINSTEIN, in 1905, went on to explain the photoelectric effect. When light is incident on a metal surface, electrons are ejected. He proposed that the energy in the beam of monochromatic light comes in parcels, $h\nu$. This quantum of energy, a photon, could be transferred completely to the electron. This explanation of the photoelectric effect added substance to Planck's earlier supposition. QUANTUM MECHANICS was born.

Solar and stellar spectral lines

The first SPECTROSCOPE, created by JOSEPH VON FRAUNHOFER in 1814, combined a prism with a small viewing telescope focused on a narrow slit. He used this instrument to view the Sun's spectrum and saw not a continuous spectrum of light, but many, many dark lines. It was later found that any chemical compound, gas or vapor, which emitted light produces its own unique spectrum.

The pattern in emission lines was established by BALMER in 1885, from studies of the hydrogen lines in the spectrum of stars. It was the theory put forward by Bohr in 1913, using Planck's ideas, which accounted for the Balmer analysis of the hydrogen spectrum. Bohr's model for the atom was based on Rutherford's model comprising a positive core, nucleus, surrounded by negatively charged electrons. However, Bohr proposed that electrons could only exist in discrete orbits. In these orbits, they did not radiate energy, but when they jumped from one orbit to another, they emitted a quantum of light. With this hypothesis, everything fell into place.

The FRAUNHOFER LINES are absorption lines from many different elements. The radiation passing through the layers in the solar atmosphere is absorbed by the atoms and ions to excite electrons to higher orbits.

Bright emission lines from PROMINENCES were recorded by Sir JOSEPH NORMAN LOCKYER in 1868. Laboratory experiments were carried out to try and reproduce these lines, but without success. He suggested that the lines were due to an element named *helium* after the Greek Sun god *Helios*. It was 25 years before the existence of helium was confirmed on Earth.

We now know that the Sun is composed mainly of hydrogen, with some helium and traces of many other elements. The spectral line patterns from these atoms and ions can be very complex, reflecting the intricacy of their atomic structure.

Atomic processes

There has been a close association between the study of the Sun and developments in atomic collision physics. The formulation of the so-called *coronal equilibrium* equations over fifty years ago pointed to the importance of excitation, ionization and recombination collisions in determining the state of the plasma and the nature of the spectral emission lines. In earlier *local thermodynamic equilibrium* models, the plasma state was determined by its temperature and the laws of statistical physics.

In the solar atmosphere, the ionization and recombination processes can usually be solved separately from the statistical equilibrium equations for the atomic processes amongst the low lying levels in the ion.

In a hot ($T > 2 \times 10^4$ K) and low electron density ($N_e < 10^{12}$ cm^{-3}) plasma, such as the outer atmosphere of the Sun and stars, it can be assumed that the spectral lines are optically thin. Low down in the atmosphere, it is necessary to solve the RADIATIVE TRANSFER equations.

The notation used is such that Fe XIV (or Fe^{13+}) is the element iron with thirteen electrons stripped off. Taking Fe XIV as an example, the ground configuration $3s^2 3p$ has two levels—$^2P_{1/2}$ and $^2P_{3/2}$—the transition between these two levels gives rise to the coronal green line at 5303 Å. The transitions between the excited configurations $3s3p^2$ and $3s^2 3p$ are at around 300–400 Å and those between $3s^2 3d$ and $3s^2 3p$ are at shorter wavelengths around 200 Å.

Spectral emission line

An ion in an excited state can spontaneously emit radiation:

$$X_j^{m+} \Longrightarrow X_i^{m+} + h\nu_{i,j} \tag{1}$$

where an atom X of charge state m, in a bound state (orbit) j emits a photon of energy $\Delta E_{i,j}$ ($= h\nu_{i,j} = hc/\lambda_{i,j}$) to arrive at a lower energy state i.

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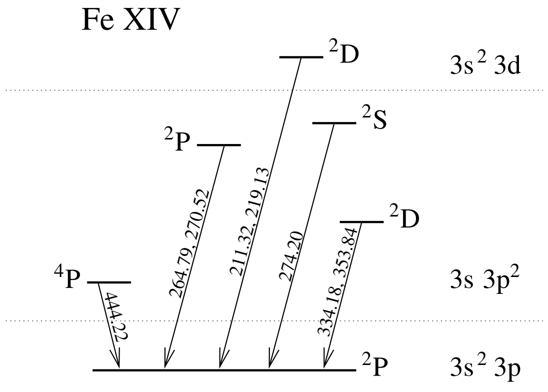

Figure 1. A diagram illustrating the strongest EUV transitions. Wavelengths are given in ångströms.

Ionization and recombination

The degree of ionization of an element is obtained by equating the ionization and recombination rates that relate successive stages of ionization.

$$N^{m+}(q_{\rm col} + q_{\rm au}) = N^{(m+1)+}(\alpha_{\rm r} + \alpha_{\rm d}). \tag{2}$$

The dominant processes in optically thin plasmas are *direct electron impact ionization* ($q_{\rm col}$)and excitation followed by *autoionization*($q_{\rm au}$); *radiative recombination* ($\alpha_{\rm r}$) and *dielectronic recombination*($\alpha_{\rm d}$). The fractional ionization ratio for each ion

$$R_m = N(X^{m+})/N(X) \tag{3}$$

is significant over a small range of temperatures and peaks at a different $T_{\rm max}$ for each ion stage. As the temperature increases, so does the ionization stage, as more and more electrons are stripped off (Arnaud and Raymond, 1992).

Direct electron impact ionization from the inner and outer shells of the ground configuration can be expressed as:

$$X_n^{m+} + {\rm e} \Rightarrow X_{n'}^{(m+1)+} + {\rm e}' + {\rm e}'' \tag{4}$$

with n and n' being the quantum state of the ions.

The process of *radiative recombination* is:

$$X_n^{(m+1)+} + {\rm e} \Rightarrow X_{n'}^{m+} + h\nu. \tag{5}$$

The inverse process is *photoionization*, which is a dominant process for many low-density astrophysical plasmas, but not for the outer atmospheres of the Sun and stars.

For the solar CORONA, the main ionization and recombination processes were originally thought to be direct electron impact ionization and radiative recombination. However, early calculations gave values of $T_{\rm max}$ for the coronal forbidden lines (due to Fe X and Fe XIV) much lower than the temperatures deduced from their spectral line profiles. This discrepancy was eventually resolved by Burgess, who showed the importance of dielectronic recombination, a process which can proceed via doubly excited autoionizing states. The process of *dielectronic recombination* is:

$$X_n^{(m+1)+} + {\rm e} \Rightarrow (X_{n'}^{m+})^{**} \Rightarrow X_{n''}^{m+} + h\nu \tag{6}$$

where an electron is captured by an ion with charge $(m+1)+$ to form a doubly excited state $(\ )^{**}$ of an ion X with charge $m+$. This ion can then either *autoionize* back again or undergo a spontaneous radiative transition of the inner excited electron to a state below the first ionization limit. Dielectronic recombination is now known to be the dominant recombination mechanism at high temperatures, for example in the solar corona. It is at least a factor of twenty higher than radiative recombination.

The inverse process to dielectronic recombination is *autoionization*:

$$(X_n^{m+})^{**} \Rightarrow X_{n'}^{(m+1)+} + {\rm e}'. \tag{7}$$

The coronal model approximation

The atomic processes which determine the populations of the low-lying levels in an atom or ion in the solar corona are *excitation by electron (e) or proton (H^+) impact*:

$$X_i^{m+} + {\rm e}\ ({\rm H}^+) \Rightarrow X_j^{m+} + {\rm e}'\ ({\rm H}^+) \tag{8}$$

and radiative processes, spontaneous ratiative decay and photoexcitation (the excitation by absorption of photospheric radiation)

For optically allowed (electric dipole transitions) which give rise to spectral lines in the UV, EUV and x-ray wavelength ranges, the *coronal model* approximation is usually valid. The population, $N_j(X^{m+})$, of the upper level, j, is determined by electron collisional excitation from the ground state i and radiative decay from j back down to i.

$$N_i(X^{m+})N_{\rm e}C_{i,j}^{\rm e} = N_j(X^{m+})A_{j,i} \tag{9}$$

where the spontaneous radiative decay rate is $A_{j,i}$ and the electron number density is $N_{\rm e}$. The electron collisional excitation rate coefficient, $C_{i,j}^{\rm e}$, is obtained by integrating the electron impact collision cross section over a Maxwellian electron velocity distribution with a temperature $T_{\rm e}$(K).

For a typical EUV transition, for example from Fe XIV, at coronal densities and temperatures, we find that $A_{j,i}$ is approximately 10^{10} s^{-1}, whereas $N_{\rm e}C_{i,j}^{\rm e}$ is around unity. The population of the upper level j is negligible in comparison with that of the ground level i.

The solution of the electron–ion scattering problem is complex and takes a great deal of computing resources. The accuracy of a particular calculation depends on two main factors. The first is the representation which is used for the target, the atom or ion, and the second is the type of scattering approximation chosen. The main approximations used for electron–ion scattering are *distorted wave* (DW), *Coulomb–Bethe* (CBe) and the more elaborate *close-coupling* (CC) approximation. The

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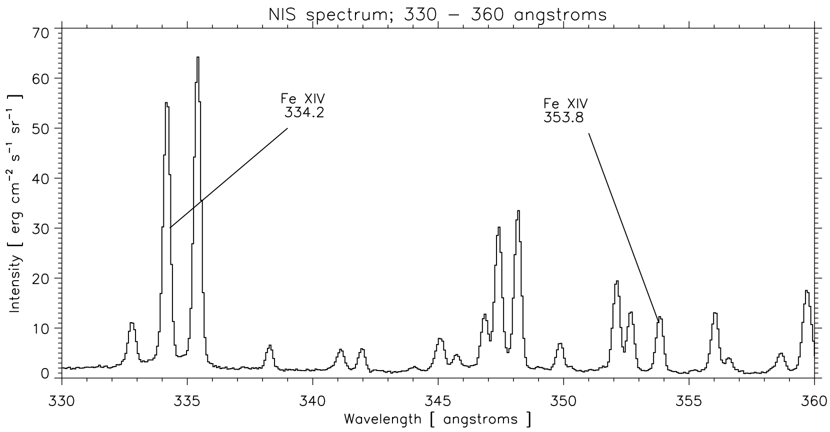

Figure 2. NIS spectrum in the range 330–360 Å taken above an active region on the solar limb. The Fe XIV 334.2 and 353.8 Å lines are clearly seen.

DW approximation neglects the coupling of the channels (target + scattering electron). Since the scattering electron sees a central field potential, the DW approximation is only valid for systems which are a few times ionized. For high partial wave values of the incoming electron, the CBe approximation is valid, when it is assumed that the scattering electron does not penetrate the target. In the CC approximation, the scattering electron sees individual target electrons, the channels are coupled and a set of integro-differential equations are solved. The CC approximation is the most accurate (better than 5%) but it is also the most expensive in terms of computing resources.

The proton collisional excitation and de-excitation rates become comparable with electron collisional processes for transitions where $\Delta E_{i,j} \ll kT_e$, where k is the Boltzmann constant. This happens for transitions between fine structure levels at high temperatures, for example the Fe XIV transition in the ground configuration: $3s^2 3p$ ($^2P_{1/2}$ - $^2P_{3/2}$).

Solar EUV spectral emission lines

The EUV wavelength range provides a wealth of spectral emission lines from many different elements and ion stages (see SOLAR SPECTROSCOPY: ULTRAVIOLET AND EXTREME ULTRAVIOLET EMISSION). Fe XIV is one of the most important diagnostic ions in the solar corona. It is abundant at a temperature of about 2×10^6 K. Transitions within Fe XIV give rise to spectral lines in the visible (green line, 5303 Å) and extreme ultraviolet (EUV) wavelength ranges. The transitions between the ground configuration ($3s^2 3p$) and excited configurations ($3s3p^2$, $3s^2 3d$) give rise to strong lines in the EUV wavelength range. These have been extensively observed with the Coronal Diagnostic Spectrometer on SOHO and can be used to determine electron density in the solar atmosphere. The transitions and observations are illustrated in figures 1 and 2.

New CC atomic calculations have recently been carried out as part of the IRON project for Fe XIV and many other coronal ions. The results provide a significant advance over previous work. In particular, many of the persistent discrepancies between observed and theoretical intensity ratios now seem to have been resolved.

Summary

The story of solar spectroscopy and the corresponding study of atomic processes has been fascinating to follow. The requirement for high accuracy atomic data to interpret astrophysical spectra has provided the stimulus for the development of new techniques in atomic physics. These new atomic data have provided the means to probe and define the physical parameters in the solar atmosphere. The two fields of study have been closely interwoven, with a very fruitful return for each. From recent solar observations, we know that the solar atmosphere is dynamic, constantly changing on all spatial scales. This poses an exciting challenge for atomic physics, to interface the theoretical solar models with atomic processes. The strong possibility exists that the solar plasma is not in equilibrium, that assumptions such as Maxwellian velocity distributions and ionization equilibrium may no longer be tenable.

Bibliography

Arnaud M and Raymond J C 1992 *Astrophys. J.* **398** 39

Fleck B and Svestka Z. (eds) 1997 *The First Results from SOHO* (Amsterdam: Kluwer)

Gabriel A H and Mason H E 1982 Solar physics *Applied Atomic Physics Theory* vol 1, ed H S W Massey and D R Bates (New York: Academic) pp 345–97

Mason H E and Monsignori-Fossi B C 1994 Spectroscopic diagnostics in the VUV for solar and stellar plasmas *Astron. Astrophys. Rev.* **6** 123–79

Vial J-C, Brocchialini K and Boumier P (eds) 1998 *Space Solar Physics* (Berlin: Springer)

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